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Guayule agronomics: establishment, irrigated production, and weed control

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Abstract

Vast amounts of information on the cultivation of guayule were generated by the Emergency Rubber Project (ERP) during World War II, but there were still knowledge gaps in many aspects of guayule growth and development. Multi-disciplinary, multi-institutional research studies from the late 1970s to the present have helped to fill these gaps. Transplanting has been and still is the most reliable method of guayule stand establishment. Direct-seeding has been successful in research plots in Texas, New Mexico, and Arizona, using seed conditioning techniques and precision planting. The consistent production of high quality guayule seed is essential for reliable establishment by direct-seeding. Although, guayule is a semiarid, drought-tolerant shrub, it must have irrigation for maximum sustained production. Guayule is not an efficient user of water, and may require from 1000 to 1300 mm of applied water (irrigation + rainfall) to attain maximum production. The quantity of irrigation water required depends primarily on the growing region and yield desired. Growers must determine a goal for economical biomass and rubber yield, and adjust inputs accordingly. Research has revealed that guayule responds to nitrogen more than any of the other major nutritional elements. The crop water stress index has been developed for guayule and is a valuable tool for growers to monitor and manage water stress and irrigation scheduling. Clipping has been demonstrated to be a viable harvest technique, and would allow growers an early return on their investment, plus it would delay the cost of stand reestablishment. Increasing salinity results in decreased biomass and rubber yield. Guayule transplants have been shown to maintain production at salinities up to 4.5–4.6 dS/m. Pendimethalin is safe for preemergence weed control in transplanted guayule. A Special Local Needs registration for pendimethalin is in place for the preemergence control of annual grasses and broadleaf weeds in Arizona. No postemergence treatments have been successful except during guayule's dormant period. Several preemergence herbicides are safe for weed control in direct-seeded guayule. However, no treatments are currently approved.

Keywords: Guayule; New crops; Irrigation; Weed control; Natural rubber; Hypoallergenic latex

1. Introduction

Guayule (*Parthenium argentatum* Gray), a member of the Compositae or sunflower family, is a profusely

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branched shrub that reaches a height of 0.3–0.9 m (Correll and Johnston, 1979). Native guayule populations are scattered throughout 300,000 km^2 of rangeland in the Chihuahuan Desert and surrounding regions (McGinnies and Mills, 1980). Indigenous U.S. stands occur in the Trans Pecos region of southwestern Texas and persist within a wide range of climatic conditions. Public attention was initially drawn to guayule in 1876 by an exhibition sent by the Mexican Government to the Centennial Exposition at Philadelphia (Hammond and Polhamus, 1965).

The Continental-Mexican Rubber Company was formed and a large factory was constructed in 1906 near Torreon, Mexico. Other factories were built in Mexico and in 1907, a facility was built at Marathon, Texas, and operated until 1916 (Perry, 1988). The sustained harvesting of entire plants (tops and roots) resulted in depletion of the native guayule populations and forced many Mexican facilities to close. Another early use of guayule was for fuel for the Mexican smelters, which depleted thousands of hectares of the shrub. The absence of guayule stands in certain regions in north and northcentral Mexico is due to this destructive process. These factors underscored the need to domesticate guayule.

Prior to World War II, studies by the private sector indicated that guayule could be produced on a variety of soils. Irrigation requirements had been determined within general limits, and cold temperature tolerances were identified (Polhamus, 1945). With the initiation of the Emergency Rubber Project (ERP) in 1942, a rapid increase in knowledge developed about the factors affecting growth and rubber accumulation in guayule. However, the primary concern was to produce rubber in the greatest quantity in the shortest time possible. This demanded the adoption of cultural methods already in place, and establishment of extensive nurseries equipped with expensive overhead irrigation systems. Above all, it involved planting guayule on irrigated land where growth could be gained as rapidly as practical. Selection of suitable land was difficult, both because of lack of complete agronomic requirements of the shrub, and the necessity of fitting guayule culture into an agriculture extended to the utmost to meet its share of the war effort. Vast amounts of information were generated during the ERP, but there were still knowledge gaps in many aspects of guayule growth and development. The greatest advances in guayule production agriculture were a result of the multi-disciplinary, multi-institutional research.

Two circumstances have added renewed interest in agronomic studies of guayule. The first is the recent widespread occurrence of Type I latex allergy to proteins in *Hevea* natural rubber (latex) products. Guayule has been demonstrated to be a source of hypoallergenic latex to replace allergy causing *Hevea* latex (Siler and Cornish, 1994). Guayule latex film has been shown to prevent the transmission of viruses and other pathogens, making it suitable for use in medical products, gloves, and condoms (Cornish et al., 1996). Second, several improved guayule germplasm lines have been released for use in breeding programs and cultivar development (Estilai, 1985, 1986; Ray et al., 1999). New studies are currently being conducted to verify that latex yields respond to various agronomic practices in the same manner as solid rubber, and that the new higher yielding, faster growing lines respond the same as the older lines used in previous studies. The objective of this paper is to review the significant agronomic findings of the ERP and the research results from agronomic studies conducted since that time.

2. Plant establishment

Two methods of establishing field plantings have been used (Hammond and Polhamus, 1965). The most widely used technique involves direct-seeding in nurseries or greenhouses for the production of seedlings for transplanting. Another method, used only on an experimental scale, involves direct field seeding. Today's production costs reflect the enormous expenses involved in the operation of nurseries and greenhouses to produce seedlings. Establishment costs could be reduced substantially with the development of successful direct-seeding techniques. Direct-seeding could reduce the cost of establishment to below US$ 400/ha versus US$ 900–1200/ha for transplanting (Bucks et al., 1986). Recent costs of transplanting guayule in Arizona are estimated to be US$ 1600/ha (D.W. Swiger, personal communication, 2003). This figure includes both greenhouse and field transplanting costs.

2.1. Seed conditioning

Successful plant establishment in the field or greenhouse depends upon good quality seed. Guayule is a prolific seed producer, blooming and setting seeds continuously throughout the growing season when moisture is available. The guayule seed is an achene with attached bracts and a pair of sterile florets (Chandra and Bucks, 1986). However, many of the seeds are either empty or not viable. The percentage of filled seed in collections made during the ERP varied tremendously (Taylor, 1946). Extremes of 0–70% were present, but percentages usually ranged from 10 to 45%.

Natural or primary dormancy in guayule seed persists in varying degrees in the mature, unthreshed condition. The delayed germination of guayule seed is attributed to two types of primary dormancy: an inner seed coat dormancy, which may last 12 months or longer, and an embryo dormancy of about 2 months (Benedict and Robinson, 1946; Emparan and Tysdal, 1957; Hammond, 1959). Research during the ERP revealed that: (1) the primary dormancy, in addition to physical barriers, could also be due to the presence of inhibitors that were partially removed by leaching during seed cleaning; and (2) intensive oxidative treatments with calcium hypochlorite, degraded the tissue surrounding the embryo and facilitated its germination (Roberts, 1946).

Seed treatments with polyethylene glycol (PEG), growth regulators, and other chemicals can enhance the planting quality of many crop and vegetable seeds (Khan et al., 1978). The beneficial effects of these treatments include rapid and uniform germination and improved seedling vigor. Partially delayed germination could be corrected by treating the seeds with a solution of calcium hypochlorite [$Ca(OCl)_2$)] or sodium hypochlorite (NaOCl), containing about 1.5% available chlorine (McCallum, 1929; Naqvi and Hanson, 1980, 1982; Tipton, 1981; Tipton et al., 1981; Jorge et al., 2002). Continuous exposure to light also overcame guayule seed dormancy (Hammond, 1959; Chandra and Bucks, 1986). Gibberellins substituted for light in completely breaking both embryo and inner seed coat dormancy, and promoted seedling emergence of non-dormant achenes under a soil cover (Hammond, 1959; Naqvi and Hanson, 1980; Tipton et al., 1981; Chandra and Bucks, 1986). This suggested that the action of gibberellins involved the hormonal enhancement of seed viability and vigor characteristics. Washing guayule seeds with water and treating with 0.5% NaOCl removed many phenolic compounds from the chaff that can cause a significant inhibition of germination and radicle growth (Naqvi and Hanson, 1982). Because, guayule seed has more than one type of dormancy, each method of breaking dormancy acts on a different dormancy factor.

A seed treatment/conditioning procedure has been developed that is currently recommended for enhancing the planting quality of guayule seed (Bucks et al., 1983; Chandra and Bucks, 1986). The procedure involves imbibing guayule seeds under aerobic conditions in a medium, containing 25% PEG (MW 8000), 10^{-4} M GA, 0.05% potassium nitrate, and 0.1% thiram fungicide adjusted to pH 8.0 with a saturated solution of calcium hydroxide. The seeds are treated for 3–4 days at 25 °C in continuous light. Guayule seed conditioning enhances both germination and the development of normal seedlings over a broad temperature range. Studies are currently under way to develop a less complicated and faster seed conditioning method (Jorge et al., 2002).

2.2. Transplants

Guayule has been successfully established using various transplanting techniques (Kelley et al., 1946; Tingey and Clifford, 1946; Erickson and Smith, 1947; Hammond and Polhamus, 1965; Tipton, 1981; Gonzalez and Rektorik, 1986). Seedlings, grown in nursery trays and transplanted into the field, grow slowly, attaining only a few millimeters of top growth and about 100 mm of root growth during the first 4 weeks after transplanting (Miyamoto and Bucks, 1985). Frequent irrigation is required for this period because of the limited root system of the transplants. The frequency under furrow irrigation may vary from 3 days to 1 week depending on air temperature, bed, soil, and water conditions. Weekly furrow irrigations of 20 mm were applied for 5 weeks to a plot at El Paso, TX, and seedling survival was more than 95% (Miyamoto et al., 1984c). Transplant survival was greater than 95% following spring plantings in a loam soil at Mesa, AZ (Bucks et al., 1984). The transplants were first furrow-irrigated with 110 mm of water immediately after planting, then were sprinkler irrigated once or twice a week for 7 weeks at 18 mm per application. Transplants have been established during spring months with 100–250 mm of water having salinity of less than 4 dS/m (Miyamoto and Bucks, 1985).

2.3. Direct-seeding

Guayule seed is small (about 1000–1500 seeds/g) and must be planted shallow for optimum emergence. Guayule seed germination begins 3–5 days after planting, followed by emergence about 10 days later (Miyamoto and Bucks, 1985). Seedlings grow slowly and produce about 10 mm of top growth and 60 mm of root growth by 2 weeks after emergence. Therefore, frequent irrigation is crucial during the first 3–4 weeks after planting to promote seed germination, prevent soil crusting, facilitate emergence, and to protect young seedlings against desiccation (Foster and Moore, 1992; Foster et al., 1999; Foster et al., 2002b). Rain showers that splash accumulated soluble salts onto the leaves of seedlings compound seedling mortality. When primary leaves appear on the seedlings, the soil surface should then be allowed to dry to reduce risk from damping-off and other seedling diseases as well as salt damage to the young seedlings. Recommended irrigation techniques for plant establishment by direct-seeding include: (1) conventional and low rate sprinklers, (2) drip, or (3) alternate row watering with furrow irrigation.

Good seed quality, seedbed preparation, and precision planting are essential for successful direct-seeding (Whitworth, 1981a,b). Direct-seeding field studies during the ERP involved planting either dry or pregerminated seed at rates of 5–15 kg/ha (Tingey, 1943, 1945a,b, 1952; Cowley, 1945a,b; Hammond and Polhamus, 1965; McGinnies and Mills, 1980). Emergence was a major problem and varied from less than 10% to over 50% with the greatest emergence occurring at the highest moisture level. Conditioned seed with germination rates varying from 56 to 92% have been used for direct-seeding in Texas and Arizona and involved seeding 100 seeds/m or about 0.5 kg seed/ha, depending on seed size and weight (Foster and Moore, 1992; Foster et al., 1993, 1999, 2002a,b; Whitworth, 1981a).

Current recommendations for direct-seeding guayule are that acceptable stands occur when seed are: (1) conditioned with PEG, gibberellic acid, and light, (2) accurately planted on the soil surface using fluid drilling or precision planting techniques, and (3) precisely irrigated being careful not to under or over irrigate (Bucks et al., 1986; Foster and Moore, 1992; Foster et al., 1999, 2002a,b). A planting rate of at least 40 seeds/m are required to obtain moderate plant populations when the initial seed germination rate is at least 60%. Seed quality, seedling vigor, and salt tolerance are still the main problems to be solved before direct-seeding could be recommended as the preferred establishment practice.

Cover crops and synthetic shade covers have been investigated for increasing seedling emergence and survival under sprinkler irrigation. Polyshade strips and cloth increased plant survival over no shading when conditioned seed were sown with a precision planter (Bucks et al., 1987). Shading by wheat increased plant survival in summer and fall treatments, but not during spring plantings. Synthetic materials decreased soil, air, and cotyledon temperatures, and increased plant water potentials versus no shade.

Although, it has usually been accepted that direct-seeding could reduce establishment costs (Bucks et al., 1986), it has never been determined whether the savings could be offset because the direct-seeded shrubs might not produce at the same level as transplants. Transplanted seedlings, grown in nursery containers in the greenhouse, are usually 7–15 weeks old, vary in height from 100 to 200 mm, and have a shallow, fibrous root system (Carranza and Ramirez, 1981; Siddiqui et al., 1982; Miyamoto and Bucks, 1985). These plants have a definite growth advantage over direct-seeded seedlings during the establishment season. Guayule has been successfully direct-seeded in field plots, but transplanting is still the most reliable method of stand establishment.

3. Irrigated production

Irrigation is a critical factor influencing guayule establishment and production. Little was known prior to 1943 about the irrigation of guayule. The irrigation amounts applied during 3 years (1943–1945) of the ERP averaged about 500 mm and formed the basis for water required for guayule production (Roberts, 1946). Higher requirements of 1000–1300 mm have been proposed by Nakayama et al. (1991). These recent values are considerably higher than the ERP standards, indicating that guayule might not be an efficient user of water.

3.1. Water quality

Water supply will determine the location of irrigated guayule production, but of more immediate concern is water quality. Salt tolerance of established guayule has been reported as higher than alfalfa and almost as tolerant as Pima (*Gossypium barbadense* L.) and Upland (*Gossypium hirsutum* L.) cotton (Miyamoto et al., 1990). However, guayule is highly susceptible to salinity at emergence and seedling stages, and tolerance at these stages is lower than carrots (*Daucus carota* L.), one of the most salt-sensitive crops currently grown in the southwestern United States.

Irrigation with waters, containing soluble salts presents a constant hazard to crop production (Longenecker and Lyerly, 1959). Those salts affect crop yields in two ways. First, excessive amounts of soluble salts in the soil limit plant growth by rendering the soil water less available to the plant. The plant roots cannot extract sufficient water for growth. Second, yields can be affected indirectly by large amounts of sodium in irrigation waters (Wadleigh and Gauch, 1944; Retzer and Mogen, 1946; Miyamoto et al., 1984c; Maas et al., 1986). Excess sodium affects growth directly by its toxic action in the plant, and also indirectly reducing soil structural properties.

Increased salinity affects guayule production by: (1) reducing dry matter production, (2) decreasing rubber production, (3) decreasing water-use-efficiency (amount of rubber produced per unit of water applied), and (4) not interacting with increased plant population to enhance rubber or resin production (Tingey, 1952; Moore and Murphy, 1979; Abrahams et al., 1984; Miyamoto et al., 1984b,c; Miyamoto and Bucks, 1985; Zittlosen and Fangmeier, 1986; Hoffman et al., 1988; Miyamoto et al., 1990; Foster and Moore, 1992; Fowler and Tinguely, 1993; Foster et al., 1999, 2002b). These studies suggest that if reduced rates of growth are acceptable and salt accumulation is minimized, then water salinity of up to 1.0 dS/m could be used for plant establishment and up to 4.5 dS/m for plant growth without risking significant mortality. The critical effect of salinity seems to be on plant mortality, indicating that survival rather than growth reduction at high levels of salinity will be the limiting factor for guayule production. Off-centered or double row planting combined with alternate row watering could help minimize salt accumulation when water of high salinity is used for irrigation.

3.2. Water stress

Early investigations confirmed that stress played an important role in rubber production. Approaches to controlling water stress focused on the theory that plant stress, caused by soil water deficits could increase rubber production. Most literature indicates that decreasing irrigation results in increased rubber content, but also causes shrub biomass reductions. The effect of irrigation on rubber yield has not been consistent. Shrub biomass and rubber yields were greatest in a sandy loam soil at the higher irrigation levels, whereas, the greatest rubber yields on a silty clay loam occurred at the lowest moisture levels (Hunter and Kelley, 1946; Bucks et al., 1984, 1985c). Rubber content increased during periods of high stress (Benedict et al., 1947). They indicated that rubber accumulation could be forced by alternating periods of low- and high-moisture stress. Water applied at 680 and 1230 mm in the second growing season produced equal amounts of shrub, and the highest rubber yield was obtained with no irrigation (Veihmeyer and Hendrickson, 1961).

A simple, reliable method was needed for following water stress so that the stress/rubber production interrelationship could be clearly defined. The crop water stress index (CWSI), developed for other economic crops, was applied to transplanted guayule by Nakayama and Bucks (1983). Shrub canopy temperature measurements based on remote infrared thermometric techniques and atmospheric vapor pressure deficits from meteorological parameters were used to relate plant water stress to the soil water status. Plant yields in a study at Mesa, AZ, were found to be negatively and linearly related to the computed CWSI range of 0.20 for the low stress to 0.75 for high stress (Nakayama and Bucks (1984). The CWSI was also related negatively to soil water content and evapotranspiration. An inverse correlation between rubber yield and seasonally averaged CWSI has also been reported (Garrot et al., 1986). The CWSI has been used for scheduling water applications for maintaining irrigation treatments (Ray et al., 1986).

Yield and crop water stress relationships have indicated that guayule grown in arid environments can be more sensitive to water stress that occurs later in the growing season than the earlier one-half of the year (Bucks et al., 1985a). Drought tolerance can permit flexibility in irrigation scheduling. However, supplemental water must be applied at high rates to increase yields and to shorten the growth cycle.

3.3. Rubber yield

Rubber is located principally in the cortical parenchyma cells of the shrubs, with two-thirds in the stem and branches, and the remainder in the roots (National Academy of Sciences, 1977). Harvesting procedures have centered on digging the whole plant to access rubber in the roots as well as the branches. Other methods have included clipping the plants at 100 mm above the soil surface and milling only the plant tops. Lloyd (1911) was the first to suggest harvesting guayule by clipping instead of digging, although the Intercontinental Rubber Company tried clipping without much success. Clipping was investigated during the ERP because this method offered the advantage of not having to replant after harvesting.

New germplasm coupled with improved agronomic practices, have significantly increased rubber yields compared with the standard USDA or Mexican germplasm (Estilai and Dierig, 1996). The University of California has released seven cultivars (CAL-1 to CAL-7) (Tysdal et al., 1983; Estilai, 1985, 1986). The Arizona Agricultural Experiment Station and the USDA/ARS jointly released six lines (AZ-1 to AZ-6), which were bred for their ability to regenerate after cutting to allow for multiple harvests, vigor of the regrowth, and bulk rubber yield (Ray et al., 1999). Rubber yields of these lines were 58–101% greater than the USDA lines.

3.3.1. Whole plant yields

Early studies found that a maximum rubber yield of 1500–1900 kg/ha was obtained after about 3 years (Kelley et al., 1946; Tingey, 1952). Recent studies have shown that shrub yield increases proportionably with increasing irrigation up to about 3000 mm for the first 2 years of growth (Bucks et al., 1984, 1985b,c; Miyamoto et al., 1984a). Thus, the quantity of water required depends upon the yield desired. The maximum shrub yields increased with length of growing season. The 2-year-old whole plant rubber yields were about 35% greater on a sandy soil (Yuma, AZ) than on a loam (Mesa, AZ). The higher yields on the sand versus the loam soil were attributed to better soil aeration, a longer effective growing season, and more vigorous plant root development. Moderate to high irrigation amounts with low nitrogen applications gave the highest biomass production that resulted in the highest rubber yields.

When guayule established from transplants was grown for two seasons, 120–160 mm/ha of water were required to produce 1000 kg of dry shrub (Miyamoto and Bucks, 1985). The annual water use of guayule for maximum shrub production was similar to that of alfalfa, but the requirement to produce 1000 kg of biomass was almost twice that of alfalfa. Water-use efficiencies have ranged from 0.70 to 0.85 kg/m^3 for dry matter, 0.045 to 0.055 kg/m^3 for resin, and 0.030 to 0.040 kg/m^3 for rubber production based on the evapotranspiration of the guayule stand (Bucks et al., 1985a).

Rubber yields from direct-seeded shrubs have been compared with transplants (Tingey and Clifford, 1946; Foster et al., 2002b). Rubber yields from most direct-seeded lines were not significantly different from transplants, and the growth period until harvest could be shortened by nearly a year by seeding directly in the field.

3.3.2. Clipped plant yields

Because a greater proportion of rubber yield is contained in the shrub branches, guayule may be commercially harvested by aboveground clipping. Clipping has been proposed to: (1) increase rubber productivity per unit area, (2) allow growers an early return on their investment, and (3) delay the cost of stand reestablishment by permitting a stand to remain productive longer (Ray et al., 1986). Limited clipping research during the ERP showed that the quality of the rubber from clipped tops was equal to that from whole plants, and rubber in the roots of clipped plants did not decrease (McGinnies and Haase, 1975). Recent clipping studies have usually supported the clipping method of harvest by showing that: (1) rubber yield was greater in clipped than whole plants, (2) sequential clipping several times would possibly increase yields compared with a single whole plant harvest at an older age, (3) clipping 2-year-old plants resulted in no yield differences between direct-seeded shrubs and transplants, and (4) salinity (especially for irrigation water above 6 dS/m) caused significant reductions in regrowth, survival, resin content, and rubber production in plant shoots and roots after clipping.

Some guayule selections responded favorably to clipping at ground level, and were capable of survival and vigorous regrowth (Estiali et al., 1988). A study conducted at Marana, AZ evaluated regrowth of three new germplasm lines (AZ1, AZ2, and AZ3) and an unreleased breeding line (G-14) following the harvest of 1- and 2-year-old plants (Coffelt et al., 2001). All lines had good regrowth except AZ1. The results from these two studies demonstrated that at least two harvests from a single planting of new germplasm lines should be possible, and that lines respond differentially in their ability to regrow.

Plants with regrowth potential are essential for multiple harvests by clipping (Estiali et al., 1988; Hoffman et al., 1988; Maas et al., 1988; McGinnies and Haase, 1975; Garrot and Ray, 1983; Bucks et al., 1985b; Ray et al., 1997; Foster et al., 1999, 2002b; Coffelt et al., 2001).

Clipping can distribute the cost of stand establishment across several harvest cycles because multiple clipping harvests would eliminate the need to reestablish shrub stands after each harvest. Results from these studies also show that lines vary in their ability to regrow following clipping, so line selection becomes important. Regrowth should be one of the critical traits evaluated by breeders and agronomists in future studies prior to releasing new germplasm.

3.4. Fertilization

Scientists in the ERP classified guayule as a low user of the major nutrients (McGinnies and Mills, 1980). Even at the high densities under which nursery seedlings were grown, the demand on the soil did not appear to be greater than for other field crops. More recent research has shown that the plant does not require high nutrient levels, except with high irrigation applications (Bucks et al., 1985c). Fertilization requirements should be based on soil fertility and general condition of the plants.

3.4.1. Transplants

Growth and rubber accumulation of transplants grown in outdoor gravel culture for 8.5 months were affected by nitrogen more than any of the other major nutrient elements (Bonner, 1944). Plants receiving most or all of their nitrogen as nitrate grew better and yielded more rubber than shrubs receiving their nitrogen as ammonium. The effect of plant spacing, fall irrigation, and fertilization on rubber production was studied during the winter at Salinas, CA, in 1-year-old guayule (Tingey and Foote, 1946). The rubber yield in shrubs fertilized in July and receiving an additional irrigation in September was 240 kg/ha versus190 kg/ha in the non-fertilized shrubs.

Plant height and width were significantly greater in the nitrogen treatments than the non-fertilized shrubs when split applications of nitrogen (4.5, 9.0, and 18.0 kg/ha) were applied to transplanted guayule in California (Cannell and Youngner, 1983). Urea, ammonium phosphate, and calcium nitrate at 112 kg of actual nitrogen/ha were applied in a guayule seed increase field at Marana, AZ (Rubis, 1983). Plant biomass in the fertilizer treatments was 10.9% greater than the control, and calcium nitrate treatments alone yielded 20% more than the control.

Although, guayule can withstand extreme drought, Bucks et al. (1985c) found that water and nitrogen applications of 2850 mm and 210 kg/ha were required to achieve the greatest production with 2-year-old shrubs. A gravel culture technique was used to study the influence of nitrogen, phosphorus, and potassium on guayule shrub growth and rubber accumulation (Thomas and Hickman, 1989). Increasing available nitrogen and potassium increased plant dry weight, but dry weight was not affected by changes in phosphorus levels.

3.4.2. Direct-seeding

The effects of fertilization on direct-seeded guayule have involved the early practice of either sowing multiple rows on wide nursery beds at heavy rates and thinning, or thickly seeding on beds in the field to establish guayule as a row crop. It should be emphasized that heavy seeding rates were used in each instance. A side dressing of nitrogen fertilizer at 280 kg/ha proved to be beneficial in a trial conducted during 1943 in California to test the feasibility of growing guayule as a row crop by direct-seeding (Hammond and Polhamus, 1965).

The effects of irrigation and fertilizer on the rubber production of thickly seeded guayule were investigated at four locations in California (Kelley et al., 1946). Guayule was seeded in rows 180 mm apart in seven-row nursery beds. After thinning, 30 kg of nitrogen, 130 kg of phosphorus, and 80 kg/ha of potassium were applied. An additional 100 kg/ha of nitrogen were applied in split applications of 50 kg each in early and late summer. The application of fertilizer did not increase rubber production. The results indicated that, for maximum rubber production, dense guayule stands were required. The optimum irrigation and fertility treatments were closely related to soil and climatic conditions. A 3-month seedling establishment period would require at least 300 mm of water and 56 kg/ha of nitrogen (Bucks et al., 1986).

4. Weed control

Weed control in guayule nurseries was one of the most expensive operations during the ERP. Nearly, 3000 people were used to hand-weed 223 ha of nurseries near Salinas, CA (Mihail et al., 1991). This labor requirement was reduced 90% by the use of close cultivation between the bands of plants, and through the development of postemergence petroleum oils. Oil sprays gave effective control of seedling grasses and some broadleaf weeds on a 472 ha plantation being cultivated for the Guayule Stockpiling Project near Crystal City, TX, in 1951 (Hammond and Polhamus, 1965). Because, the selective weed oils have a limited spectrum of weed control and are not cost effective, more recent research has focused on the evaluation of modern herbicides (Table 1). These compounds have been applied for weed control in transplanted and direct-seeded guayule. The more effective treatments will be discussed in the following sections.

4.1. Transplants

Guayule is a poor competitor against annual and perennial broadleaf and grass weeds. In a commercial situation, guayule will not be harvested for at least two growing seasons.

Therefore, growers will need effective, economical weed control during establishment, and up to the time when the shrubs have grown too large to permit mechanical cultivation.

4.1.1. Preemergence treatments

Studies in Arizona and California showed that trifluralin was a promising preemergence treatment for controlling annual broadleaf weeds and grasses (Siddiqui et al., 1982; Elder et al., 1983; Kidd, 1983). Several preplant incorporated herbicides were tested in field plots in New Mexico (Whitworth, 1983) (Table 2). Fluridone is an excellent broad-spectrum herbicide that gave 91% weed control with no injury to guayule. DCPA, pendimethalin, diuron, simazine, and trifluralin also were promising treatments. The results of herbicide evaluation trials in Australia indicated that successful stand establishment would only be achieved by transplanting with preemergence weed control (Milthorpe et al., 1991). A preplant incorporated tank mix application of oxyfluorfen plus oryzalin at a rate of 2 + 2 kg ai/ha gave excellent weed control for a full spectrum of weeds for at least 6–8 months. Preemergence treatments of isoxaben, pendimethalin, and trifluralin were tested at Fort Stockton, TX for weed control in

Table 1
Common and chemical names of herbicides used with guayule

Common name	Chemical name
Bensulide	*O*,*O*-Bis(1-methylethyl) S-[2-[(phenylsulfonyl)amino]ethyl] phosphorodithiolate
Bromoxynil	3,5-Dibromo-4-hydroxybenzonitrile
DCPA	Dimethyl 2,3,-6-tetrachloro-1,4-benzenedicarboxylate
Diruon	*N*′-(3,4-dichlorophenyl)-*N*,*N*-dimethylurea
Fluridone	1-Methyl-3-phenyl-5-[3-(trifluoromethyl)phenyl]-4(1*H*)-pyridinone
Glyphosate	*N*-(Phosphonomethyl)glycine
Hexazinone	3-Cyclohexyl-6-(dimethylamino)-1-methyl-1,3,5-triazine-2, 4(1*H*, 3*H*)-dione
Isoxaben	*N*-[3-(1-Ethyl-1-methylpropyl)-5-isoxazolyl]-2,6-dimethoxybenzamide
Metolachlor	2-Chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl) acetamide
Oryzalin	4-(Dipropylamino)-3,5-dinitrobenzenesulfonamide
Oxyfluorfen	2-Chloro-1-(3-ethoxy-4-nitrophenoxy)-4-(trifluoromethyl)benzene
Paraquat	1,1′Dimethyl-4-4′-bibyridinium ion
Pendimethalin	*N*-(1-Ethylpropyl)-3,4-dimethyl-2,6-dinitrobenzenamine
Prodiamine	2,4-Dinitro-N^3, N^3,-dipropyl-6-(trifluoromethyl)-1,3-benzenediamine
Simazine	6-Chloro-*N*,*N*′-diethyl-1,3,5-triazine-2,4-diamine
Trifluralin	2,6-Dinitro-*N*,*N*-dipropyl-4-(trifluoromethyl)benzenamine
2,4-D	(2,4-Dichlorophenoxy) acetic acid

Table 2
Weed control and response of transplanted guayule to preplant, soil incorporated herbicides during 1979 in New Mexico[a]

Herbicide	Rate (kg/ha)	Weed control (%)	Biomass (% of check)
DCPA	9.0	60	127
Fluridone	0.5–1.8	91	104
Metolachlor	1.1–2.2	46	117
Pendimethalin	0.6–1.1	68	132
Diuron	1.1–1.7	83	85
Hexazinone	1.1–2.2	82	51
Simazine	1.1–2.2	87	79
Trifluralin	0.6–1.1	69	89

Source: Whitworth (1983).

[a] Values are averages of both greenhouse and field experiments. Biomass was based on stand only in some experiments and whole plant dry weight in others. Weed control was recorded as percent control compared with the untreated check.

Mexican-bulk transplants (Table 3). Shrub biomass, rubber and resin content, and rubber and resin yield in the treatments were all equal to or greater than the control.

With the support of the preceding studies, a Special Local Needs registration has been issued for the use of pendimethalin (Prowl 3.3 EC) for preemergence control of most annual grasses and certain broadleaf weeds in transplanted guayule in Arizona (Arizona Department of Agriculture, 2003). Pendimethalin may be applied for short-term (4 months) or long-term (6–8 months) weed control at rates of 5.6 and 11.2 l/ha, respectively. The herbicide should be applied after transplanting as band or broadcast sprays, without allowing the spray to contact guayule leaves, shoots, or buds. Pendimethalin can also be applied through chemigation systems as a supplemental weed control operation.

4.1.2. Postemergence treatments

Postemergence, over-the-top herbicide treatments are toxic to guayule transplants during periods of active growth. No herbicides are labeled for postemergence weed control in guayule. Unshielded glyphosate applications resulted in high-guayule mortality (Siddiqui et al., 1982; Ferraris, 1986). The recommended treatments were paraquat and glyphosate applied as shielded sprays when the shrubs were dormant. Shielded band sprays of paraquat in the spring to control winter weeds, and glyphosate in the fall to control summer weeds, supplemented by hand weeding have been successful in Australia (Ferraris, 1986). It was proposed to band-spray oryzalin over the beds and incorporate trifluralin in the furrows after harvest by clipping.

Broadcast sprays for weed control in established guayule should be applied to dormant shrubs, and spot or individual plant treatments can be used for localized weed infestations. Glyphosate, oryzalin, and oxyflurofen applied as directed sprays to dormant guayule shrubs effectively controlled established weeds and were not toxic to the shrubs (Ferraris, 1986; Foster et al., 1986; Milthorpe et al., 1991). Postemergence broadcast sprays of glyphosate, 2,4-D, and bromoxynil

Table 3
Effect of preemergence herbicides on Mexican bulk guayule transplants 10 months after treatment in 1991 and 1992 near Fort Stockton, TX

Herbicide	Rate (kg ai/ha)	Biomass (kg/ha)		Rubber yield (kg/ha)	
		1991	1992	1991	1992
Isoxaben	0.6	2453 a*	3166 a	119 a	233 a
Isoxaben	1.1	2224 ab	3216 a	105 ab	230 a
Isoxaben	2.2	2181 ab	3118 a	105 ab	225 ab
Pendimethalin	1.1	1873 bcd	2589 bcd	101 ab	193 cd
Pendimethalin	2.2	1925 bcd	2715 bc	99 ab	199 bcd
Pendimethalin	4.4	2020 bc	2894 ab	95 b	215 abc
Trifluralin	1.1	1765 cd	2105 ef	87 bc	157 e
Trifluralin	2.2	2084 abc	2269 de	96 b	174 de
Trifluralin	4.4	2082 abc	2352 cde	106 ab	173 de
Control	0	1644 d	1793 f	71 c	129 f

Source: M.A. Foster, Texas A&M University Agricultural Research Station.

* Means within columns followed by the same letter are not different according to Fishers protected least significant difference at the 5% level.

Table 4
Effect of preemergence herbicides on seedling emergence for guayule direct-seeded on a Delnorte very gravelly loam near Fort Stockton, TX

Herbicide	Rate (kg/ha)	Guayule seedlings/m (days after planting)		
		10	25	40
DCPA	4.5	37 a*	26 a	22 ab
DCPA	9.0	37 a	23 a	20 ab
DCPA	11.0	36 ab	27 a	22 ab
Pendimethalin	0.3	34 ab	26 a	23 ab
Pendimethalin	0.6	34 ab	25 a	23 ab
Pendimethalin	1.1	30 ab	22 a	17 ab
Prodiamine	0.3	34 ab	24 a	21 ab
Prodiamine	0.6	27 ab	18 a	16 ab
Prodiamine	1.1	23 b	13 a	10 b
Control	0	42 a	28 a	24 a

Source: M.A. Foster, Texas A&M University Agricultural Research Station.

* Means within columns followed by the same letter are not different according to Fisher's protected least significant difference at the 5% level.

were applied to a dormant guayule stand with no shrub injury (Foster et al., 1989).

4.2. Direct-seeding

As mentioned in previous discussion (Section 2.3), guayule is difficult to establish by direct-seeding because the seedlings grow slowly, and at the same time, cannot compete effectively against emerging weed seedlings. An effective preplant or preemergence herbicide is required for optimum stand establishment. Several preplant, soil incorporated herbicides have been evaluated in New Mexico (Whitworth, 1981b, 1983; Boyse et al., 1983). Only bensulide, DCPA, and pendimethalin demonstrated adequate selectivity on direct-seeded guayule.

Preemergence treatments of DCPA, pendimethalin, and prodiamine were tested on a Dalby clay at Fort Stockton, TX (Foster et al., 1993). Guayule seedling establishment with DCPA (4.5 and 9.0 kg ai/ha), pendimethalin (0.3 kg ai/ha), and prodiamine (0.3 kg ai/ha) was not significantly different from the control in 1991. An unpublished study by Foster, conducted on a Delnorte very gravelly loam at Fort Stockton, confirmed the adequate selectivity of DCPA and pendimethalin as preemergence weed control treatments for direct-seeded guayule (Table 4).

DCPA (4.5, 9.0, and 11.0 kg/ha), bensulide (2.2, 3.4, and 4.5 kg/ha), and pendimethalin (0.6, 1.1, and 2.2 kg/ha) were applied as preplant incorporated treatments on a Casa Grande sandy clay loam before direct-seeding at Maricopa, AZ (Foster et al., 2002a). Pendimethalin was safe for use in guayule direct-seeding. This herbicide has a broad spectrum of weed control, and is used widely by growers for weed control in other crops.

5. Summary

Transplanting has been and still is the most reliable method of guayule stand establishment. Direct-seeding has been successful in research plots in Texas, New Mexico, and Arizona using seed conditioning techniques and precision planting. Direct-seeded plants were shown to produce rubber yields comparable to transplants grown under the same field conditions. However, some problems must be addressed before direct-seeding can become a reliable commercial establishment technique. The consistent production of high-quality guayule seed with germination percentages above 75% are essential for direct-seeding.

Although guayule is a semiarid, drought-tolerant shrub, it must be irrigated for maximum sustained production. Guayule is not an efficient user of water. It may require from 1000 to 1300 mm of applied water (irrigation + rainfall) per year to attain maximum production. Rubber yields in transplants were shown to increase proportionally with increasing irrigation up to almost 3000 mm for two growing seasons. The quantity of water required depends primarily on the growing region and yield level desired. The crop water stress index has been developed for guayule and will be a valuable tool for growers to monitor and manage water stress and irrigation scheduling. Growers must decide what the economical biomass/rubber yield should be, and adjust their irrigation and fertilizer inputs accordingly.

Clipping in transplanted and direct-seeded stands can distribute the cost of stand establishment across several harvest cycles since multiple clipping harvests would eliminate the need to reestablish shrub stands after each harvest. This translates to lower stand establishment costs. Results have shown that different guayule lines vary in their ability to regrow following clipping, so line selection becomes important when this type of harvesting system is to be used. Regrowth following clipping should be one of the critical traits evaluated by breeders and agronomists in future studies prior to releasing new germplasm.

Increasing salinity decreases biomass and rubber yield. Guayule transplants have been shown to maintain production at salinities up to 4.5–4.6 dS/m. The major salinity problem may be one of survival and establishment, and not necessarily growth reduction. Direct-seeding guidelines to minimize salt damage to susceptible seedlings include sprinkler irrigation for germination and emergence, followed by furrow irrigation for plant maintenance and production.

Research has revealed that guayule does not require high nutrient levels except with high irrigation applications. Shrubs responded more to nitrogen than any other major nutritional elements. Guayule production on soils with inherently high nitrogen levels may not require added fertilizer inputs.

Trifluralin and pendimethalin are safe for preemergence weed control in transplanted guayule. A special local needs registration for pendimethalin, has been granted for the preemergence control of broadleaf and grass weeds in Arizona. No postemergence treatments have been successful as over-the-top sprays except during the guayule dormant period. DCPA (9.0 kg ai/ha), bensulide (3.4 kg ai/ha), and pendimethalin (0.6–1.1 kg ai/ha) can be used for preemergence weed control in direct-seeded guayule. No pre- or postemergence treatments are currently labeled for use in direct-seeded plant establishment.

Continued research on the agronomic practices to produce guayule is needed to address issues, such as new uses, germplasm, and herbicides that might affect the results from previous studies and recommendations to growers.

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